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MILLIMETER-WAVE GENERATION WITH ELECTRON-BEAM DEVICES

A CRITICAL SURVEY OF THE STATE OF THE ART

by Bernhard Kulke

Electronics Research Center
Cambridge, Mass.





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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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MILLIMETER-WAVE GENERATION WITH ELECTRON-BEAM DEVICES

A Critical Survey of the State of the Art

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SUMMARY

While the state of the art in millimeter-wave generation is still dominated by linear-beam tubes of conventional design, further technological development of these devices faces increasingly difficult fabrication problems. These problems are avoided in another class of devices where a periodically deformed beam is made to yield energy to the electric fields supported by a smooth wave guide. Periodic-beam tubes, such as the cyclotron maser, have already equalled or surpassed the power versus frequency frontier of periodic-circuit devices, and the prospects for further development are very good.

I. INTRODUCTION

Notwithstanding the rapid rate of progress in developing the power/frequency capabilities of solid-state sources, it is generally recognized that, at the present time, tubes still hold a strong competitive edge in the generation of electromagnetic signals at high frequencies and for high power levels. The purpose of this Technical Note is to assess the capability of beam-type devices for coherent power generation in the millimeter-wave region. While heavy emphasis has been placed on measured results, i.e., devices with demonstrated practical value, we have also attempted not to overlook the potential of devices where the dearth of experimental data may be due to a lack of development effort. In all cases, we have highlighted important evolutionary stages so that one may gain some idea of the amount of development effort that has already been expended, of the results achieved, and hence, of the probable rate of return on any additional effort.

A reasonably complete set of references has been compiled. Our rationale in the selection of entries was two-fold:

1. To support our own comments and conclusions about current devices
2. To provide the interested reader with an adequate guide for making his entry into the detailed literature.

Further references may be found in some similar surveys and review papers published recently (Refs. 1-3).

Electron-beam devices may roughly be divided into three major groups. The first of these, periodic-circuit devices, includes the well-known, conventional travelling wave tubes (TWT), backward-wave oscillators (BWO), and magnetrons. It is interesting to note that the current power/frequency frontier still is largely dominated by these tubes (Figures 1 and 2). However, they are clearly being pushed to the practical limit of fabrication and beam-formation techniques that are required when a high-density, thin beam must be brought close to a delicate slow-wave structure. Reflex klystrons for millimeter-wave use will also be mentioned in this group, as they share the problem of diminishing dimensions with the periodic-circuit devices. DC-pumped transverse wave amplifiers seemed, at first, to have strong millimeter-wave potential and, consequently, they have received much attention by a number of researchers, albeit with limited success. These tubes also depend on a periodic structure for interaction with the electron beam.

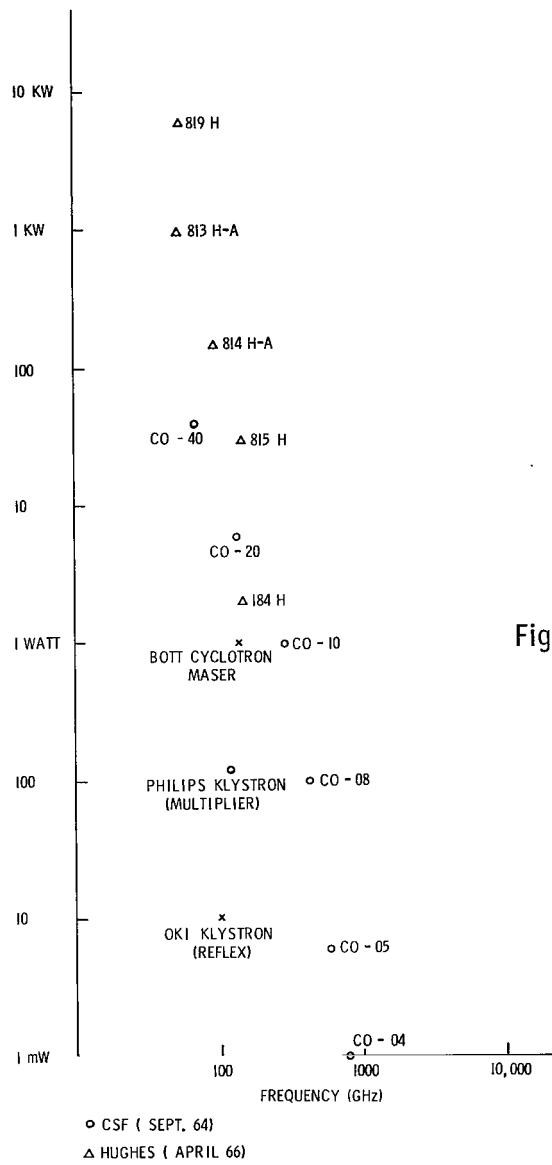


Figure 1. - Frontier Devices in cw mm Wave Generation

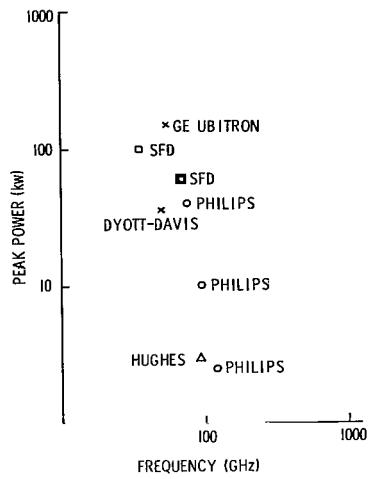


Figure 2. - Frontier Devices in Pulsed mm Wave Generation

The circuit fabrication problem can largely be avoided by trading the periodic circuit for a periodic beam. This gives rise to a second class of devices -- periodic beam devices. Some tubes of this type (e.g., the Ubitron and the cyclotron maser) have already equalled or surpassed the present power/frequency frontier held by the periodic-circuit devices, and the prospects for further progress are very good.

Finally, a third class of tubes -- beam harmonic couplers -- makes use of the inherent nonlinearity of an electron beam operating as a transmission line. The beam is bunched at some (low) frequency and harmonic power is extracted downstream at a higher frequency (e.g., millimeter waves). The problem of extracting harmonic power efficiently from the beam has been approached in many different ways, giving rise to such devices as undulators and Cerenkov couplers.

Representative examples from all these groups will be discussed below and conclusions will be drawn as to which of these devices deserve significant development effort in the future.

II. PERIODIC-CIRCUIT DEVICES

The present frontier in the power versus frequency plane is dominated by periodic-circuit devices, despite the fact that these date back to the invention of the magnetron during World War II. (The purpose of using a periodic structure is to delay an electromagnetic wave sufficiently to achieve synchronism and, hence, cumulative interaction with an electron beam drifting alongside the structure.) This group of devices includes such conventional tubes as TWT's, BWO's, and magnetrons. Klystrons are also mentioned here, since there is no profound difference between the operation of a klystron, especially of the distributed-interaction variety, and a severed TWT. Considerable research effort has recently been put into dc-pumped transverse-wave parametric amplifiers, though with very limited success. These tubes also use periodic structures.

Conventional Tubes

A recent review paper by Forster (Ref. 1) contains a comprehensive summary of the state of the art with regard to conventional periodic-circuit devices, including both linear-beam (O-type) and crossed-field (M-type) tubes. From the paper, it is evident that the Hughes Research Laboratories and the Compagnie Générale de Télégraphie sans Fil (CSF) are currently setting the standards in the power/frequency race with their O-type backward-wave oscillator tubes. Figure 1 shows plotted CW power versus frequency for their latest model tubes. These data provide a convenient measure with which to compare the potential or measured performance of other tube types. Figure 2 gives pulsed power versus frequency for some current state-of-the-art devices.

The generation of millimeter-wave power with periodic-circuit techniques is limited primarily by three factors. First, it is difficult and costly to fabricate the delicate slow-wave structures that are necessary; typically these require 1-micron tolerances. Second, a small-diameter, high-density beam must be generated and brought close to the structure; the required large convergence ratios result in a large thermal velocity spread. Third, the ohmic losses of the slow-wave structures, together with the small interaction impedances, become a significant factor in raising the start-oscillation current. Despite these limitations, the power/frequency profile of BWO's is being pushed upward constantly, and there appears to be no fundamental physical threshold to stop this progress. A good insight into the technology of building periodic-circuit tubes for the millimeter-wave range is given in a number of recent conference papers (Refs. 4-8).

The interaction of an electron beam with a slow-wave structure near cutoff leads to a type of instability that has been observed in high-power TWT's for some time and that recently has been analyzed by Bahr (Ref. 9). This type of oscillation has been exploited in the Ladderton tube (Ref. 10). In one experiment with such a tube, a 2.5-kV strip beam was coupled to a ladder structure near cutoff, with a resultant output of 10 watts cw near 50 GHz. The novelty of this tube seems mainly to be in a possible fabrication advantage connected with the operation near cutoff, because this implies that the periodic spacing of the slow-wave structure may be larger than it would be for within-passband space-fundamental operation.

Magnetrons are probably the oldest millimeter-wave generators in terms of their (usually unwanted) higher mode output. The possibility of enhancing the harmonic output of magnetrons was first suggested by Lamb (Ref. 11) and was recently demonstrated by Strauss and Kroll (Ref. 12). Since good performance evidently can be obtained by simply modifying the resonant structure of a production tube to enhance a desired higher order resonance, this approach appears very promising. Even for fundamental-frequency operation, magnetrons have been improved to provide sizable pulsed power output well into the millimeter-wave region. Such tubes have been built by Philips-Eindhoven (Refs. 13-14) and SFD Laboratories up to 95 GHz (see Figure 2). Although there appears to be no basic physical threshold to bar the continuing extension to higher frequencies of fundamental magnetron operation, it appears that further progress will again be limited by technological problems similar to those mentioned earlier in connection with BWO's.

Reflex klystrons have generated millimeter-wave power up to 150 GHz, but their power versus frequency profile is generally lower in that part of the spectrum than that of distributed-interaction tubes. The main problems here are cathode loading, voltage breakdown, and effective heat dissipation. Two-cavity frequency-multiplier klystrons, however, have performed rather well; these tubes are discussed in Section IV.

Transverse-Wave Devices

When the problems of raising the power/frequency limit of conventional klystrons, TWT's, and BWO's began to become more difficult, there was a strong incentive to look for alternative methods of generating coherent high-frequency power, which would still be based on well established electron-beam technology.

With the invention of the Adler tube in 1958, a frequency-independent gain mechanism became available. It was based on parametric amplification of the transverse motion of beam electrons. This raised great expectations for millimeter-wave applications, especially when the need for a pump source at twice the signal frequency was eliminated by the discovery of dc pumping, i.e., amplification by passage of the modulated beam through an appropriate electrostatic or magnetostatic field pattern. The development of linear-beam transverse-wave devices, particularly dc-pumped devices, is considered in detail in the Appendix. The basic problem with the devices that have been built and tested seems to be one of beam control. A relatively strong modulation of the beam boundary is to be expected, of course, since the beam interacts with transverse electric fields. In addition, however, continuous expansion of the beam takes place in the pump region even under dc conditions, because the rate of internal rotation of the dc beam under practical focussing conditions is never far removed from the cyclotron frequency. These two factors combine to make beam interception a limiting factor on measured gain in practically all the transverse-wave experiments reported in the literature. Efforts to control the beam-expansion mechanism by increasing the space-charge density have failed so far, theoretical predictions to the contrary. Apparently the beam can, at most, be brought into an unstable equilibrium state that is easily upset in the presence of any rf debunching forces.

Since precise beam control has already been found to have decisive importance in the existing linear-beam millimeter-wave tubes, it seems doubtful, just on these grounds, whether dc-pumped tubes will ever become serious contenders for high-power millimeter-wave generation. An additional point is that dc-pumped tubes, like conventional linear-beam tubes, require periodic structures, so that one gains little, if any, fabrication advantage in going to these tubes.

While transverse-wave tubes utilizing periodic circuits clearly have not proved to be very successful, the interaction between a transversely modulated beam and a smooth structure has produced very useful results. Devices based on this type of interaction are described in Section III.

In conclusion, it appears that conventional periodic-circuit devices have been pushed close to their technological limit for fundamental operation (TWT's, BWO's, magnetrons), although moderate progress still can be expected from further refinement of the existing techniques of beam formation and structure fabrication. Harmonic operation of magnetrons looks quite promising, although noise may be a problem here. DC-pumped transverse-wave tubes did not live up to the high expectations raised by the early theory, mainly because of unforeseen, but basic, problems of beam control; further development effort on these tubes is probably not worthwhile.

III. PERIODIC BEAM-DEVICES

The difficulty of fabricating delicate periodic structures for millimeter-wave tubes and the problem of cooling these structures during interaction with a high-density electron beam make it desirable to do away with slow-wave structures altogether. The purpose of these structures is to support a slow electromagnetic wave that propagates in synchronism with the beam electrons. However, an equivalent effect is produced when a periodically deformed beam is allowed to interact with a smooth waveguide. The wave propagating in a smooth guide has a phase velocity greater than the velocity of light and, for this reason, these devices are often called fast-wave tubes. The required synchronism condition is best understood in terms of an electron moving with the beam and rotating about the beam axis at the cyclotron frequency. The wave slips past the moving beam with a relative velocity such that the rf phase of the electric field seen by the rotating electron remains invariant. To extract energy from the beam, more electrons must, on the average, be decelerated than are accelerated; it is therefore necessary to have some bunching of the beam around the position of the most decelerated electron. In the helical-beam case (discussed below) this bunching is thought to be accomplished in part by the magnetic-field component of a TE_{10} mode propagating in a smooth waveguide. Other devices to be described make use of undulating or scalloped beams.

It will be recognized that periodic-beam devices are also transverse-wave devices in the sense that any periodic deformation of the beam can be analyzed as a superposition of the transverse normal modes. Conversely, some of the transverse-wave devices discussed in Section II will typically exhibit periodic (helical) beam trajectories. The essential point concerning the periodic-beam devices discussed here, however, is that the beam interacts exclusively with an unretarded ("fast") wave supported by, or within, a smooth waveguide, so that the only periodicity in the system is that contained on the beam itself.

Helical-Beam Devices

Periodic-beam devices were first suggested by Kleinwächter (Ref. 15) and Müller (Ref. 16) and other authors have since contributed to the theory (Refs. 17-24). The first practical realization of such a device was the Helitron oscillator (Ref. 25) in which a helical beam was made to interact with a 2-GHz TEM wave propagating along a smooth four-wire line. Pantel (Refs. 26-29) built and operated a helical-beam device at S-band that he called a cyclotron-resonance backward-wave oscillator.

(The term "cyclotron resonance" has since come to be applied loosely to any device in which orbital motion of electrons drifting in a magnetic field takes place, since such motion does occur, naturally, at the cyclotron frequency.) In Pantell's tube, a hollow cylindrical beam was injected axially into a magnetic field that was directed along the axis of a smooth rectangular waveguide. The electrons then spiralled about the waveguide axis at the cyclotron frequency and so gave up energy to the TE_{10} fields in the guide. However, later attempts to scale the S-band tube into the millimeter-wave region failed (Ref. 30), the main problem being the appropriate beam injection to achieve the desired trajectory in the presence of the strong magnetic field necessary for millimeter-wave operation. The same difficulty was experienced in a similar experiment performed elsewhere (Ref. 31).

The beam injection problem was successfully solved by Bott (Ref. 32) who built what could be considered an improved version of Pantell's tube. This type of device has come to be called a cyclotron maser. Bott's device worked with a magnetic field configuration such as that achieved by two coaxial solenoids, in which a spatially uniform low-field region converges to a spatially uniform high-field region. A solid beam is injected obliquely into the low-field region and proceeds to describe a helical trajectory as it drifts towards the high-field region. The correct shape of the trajectory is thus established before the beam enters a strong magnetic field. In changing from one region to another, the transverse kinetic energy of the beam electrons is increased, at the expense of the axial energy, by a factor equal to the ratio of the magnetic field intensities. At the same time, the electrons now orbit at the cyclotron frequency corresponding to the high-field region, and this frequency may be in the millimeter range. Energy is coupled out as the spiralling beam interacts with the transverse-electric fields of a cavity resonator.

Bott's original device delivered 1 mW cw near 300 GHz. Hirshfield and Wachtel (Ref. 33) later modified the device by injecting the beam axially into the low-magnetic field region and then generating a helical trajectory by passing the beam through a region of superimposed transverse magnetic field that twisted with the beam, i.e., a "corkscrew modulator." By this method they were able to generate about 10 mW near 5.8 GHz. Later, Bott (Ref. 34) reported 1-watt outputs at frequencies ranging from 80 to 140 GHz, with 2 percent efficiency; he obtained this by using Hirshfield and Wachtel's approach on his earlier device.

Considerable effort has been expended to arrive at an analytical model which would correctly describe the gain mechanism

involved in helical-beam devices. Chow and Pantell's original wave-type analysis (Ref. 29) gave good agreement with their measured data, but the bunching mechanism they postulated was found by others to be somewhat incomplete, both on the basis of analytical arguments (Ref. 35) and computer studies (Ref. 36). Hirshfield and others (Refs. 37, 38) have recently published analyses of cyclotron-resonance interaction, considered from the viewpoint of both statistical and quantum mechanics. A simple and adequate model for the gain mechanism is still lacking, however.

As can be seen from Figure 1, the cyclotron maser to date performs very close to current state-of-the-art devices, even in its non-optimized laboratory versions. The only drawback of this device is the relatively high magnetic fields required (100 kG at 300 GHz), but, with the increasing availability of superconducting solenoids, such high fields are no longer impractical. In any case, some trade-off appears possible between the required magnetic field intensity and the beam voltage. One method of achieving millimeter-wave output from a cyclotron-resonance device, without using excessive magnetic field strengths, is based on using coupler fields which form a periodic array around the circumference of the helical beam. Energy is then extracted from the electron orbits at some multiple of the cyclotron frequency, and millimeter-wave generation becomes possible with moderate magnetic fields. The appropriate coupling-field pattern can be obtained, for example, from a conventional magnetron anode, or by letting the beam excite a TE_{n11} mode (having n azimuthal variations) in a circular-cylindrical cavity. The feasibility of this method was demonstrated by Dain and Thompson (Ref. 39) who used a magnetron anode to obtain the 6th harmonic from a beam that had been transversely modulated at 600 MHz by means of a Cuccia coupler. However, this approach has not yet produced any results in the millimeter-wave range, although work is in progress (Ref. 40) to build a device where a large-diameter rotating beam will give up energy to the TE_{n11} field of a resonant cavity, at a frequency that is the n th harmonic of the cyclotron frequency.

Strong magnetic fields are easiest to generate in small volumes, and this fact led to still another approach towards easing the magnetic field requirement for generating millimeter waves with helical beam tubes. Bobroff and Haus (Ref. 41) proposed the "cycloidotron"; this is essentially a device like Pantell's tube, except that the periodic beam trajectory is formed in crossed E and H fields, with the magnetic field transverse to the beam axis and thereby extended over a relatively small volume. This tube was never reduced to practice, however.

Helical-beam interactions are inherently well adapted for use with open-resonator (and hence, high-Q) structures, and therefore seem to be well-suited to the generation of quasi-optical submillimeter radiation. Feinstein (Ref. 42) has generated 5 kW peak at 35 GHz by extracting power from a helical beam in an open-resonator field pattern, and his results and techniques should scale readily to shorter wavelengths.

In summary, it appears that despite some initial setbacks, helical-beam devices have evolved to the point where they can compete strongly with, or even surpass, the more conventional state-of-the-art devices in millimeter-wave generation. Very promising at this time are the open-resonator quasi-optical interactions, and the harmonic-generator devices. The simple cyclotron maser also merits further attention in view of the fact that 100-kG steady magnetic fields today are no longer as impractical as they once were.

Undulating-Beam Devices

A very successful embodiment of the periodic-beam concept is represented by the Ubitron (Ref. 43). In this device, a cylindrical beam is injected axially into a rectangular waveguide propagating the TE₁₀ mode, and the beam is then made to undulate by means of a periodic, transversely directed, magnetic field pattern. Although no simple model has yet been found to fully explain the observed interactions, the device has proven to be a highly efficient (30 percent) amplifier at S band, and it has been scaled successfully to operate in the millimeter-wave region, delivering 150 kW of peak power at 55 GHz (Ref. 44).

However, it is doubtful whether much higher frequencies can be achieved with this device, because the periodic array of magnets must become smaller and smaller, with fields getting larger, and magnetic saturation and leakage become limiting factors (Ref. 45). Also, as is the case with other periodic circuits, the beam perturbation dies off exponentially away from the magnetic structure, so that beam coupling decreases as magnetic-circuit periodicity increases. Thus it appears that the Ubitron at 55 GHz is probably very near its upper frequency limit, and that further progress would be expected mainly in going towards higher power levels.

Undulating (cycloidal) motion of an electron beam can also be achieved by injecting it into a region of crossed electric and magnetic fields. This is done in a magnetron, for example, in which the periodic beam then interacts with the traveling fields of a slow-wave structure. The crossed-field approach has the advantage of generating the undulating beam trajectory without the need for a periodic electrostatic or magnetostatic field, and for this reason it is well adapted to millimeter-wave devices.



Under certain conditions it is possible to achieve cumulative interaction between the undulating beam and a TEM wave propagating peripherally in the space between cathode and anode. In so-called "smooth-anode magnetrons," this effect is enhanced by using a smooth cylindrical anode, rather than the usual re-entrant slow-wave structure. The effect is unchanged, of course, when the cylindrical geometry is developed into a planar one. It was first investigated in this form by Swift-Hook and Reddish (Ref. 46) for possible millimeter-wave application. A tube built by Stevenson and Reddish (Ref. 47) produced a cw-output power of about 5 watts near 20 GHz, and a later device by Woollett and Reddish (Ref. 48) gave 4 watts at 28 GHz. A similar tube was built by Suematsu et al. (Ref. 49) for operation at 36 GHz, but it yielded only 50 mW. A basic limitation of these tubes is that for high power at high frequencies one must apply tens of kilovolts over the anode-sole distance which is of the order of a few mils, and that, consequently, breakdown occurs. The magnetic field required is also relatively large (25 kG for operation at 100 GHz).

However, this type of tube is potentially very efficient because of the simple built-in phase selection of "favorable" electrons, i.e., only those electrons that are phased to give up energy to the field survive in the interaction space. This type of tube (sometimes also called a cyclotron-resonance tube) appears to be well-suited for operation in the millimeter wave region.

Scalloped-Beam Devices

A recent addition to the class of periodic-beam devices is the scalloped-beam tube of Dyott and Davies (Ref. 50). In this device, the beam periodicity is produced by the natural scalloping of a shielded-gun beam that travels inside a waveguide of circular cross-section. The operation can be explained in part by interaction between the fundamental space component of the rippled beam and the forward-traveling TM₁₀ waveguide mode. However, a complete small-signal theory so far does not exist. With a beam voltage of 80 kV, the scalloped-beam tube has developed a peak power of 36 kW near 40 GHz, at 7 percent efficiency, and is thus quite competitive with state-of-the-art devices (Figure 2).

However, this tube requires a relatively large magnetic field strength. Typical numbers are an 80-kV beam voltage with a 23-kG focussing field, for operation at 40 GHz. Since the magnetic field generally scales linearly with frequency in periodic-beam devices, the excessive field requirements of

scalloped-beam tubes probably eliminate them as potential millimeter wave generators, at least in the present form of the Dyott-Davies tube.

Swept-Beam Devices

It is characteristic of electron beams that they cannot be accelerated to velocities beyond the velocity of light, because of the relativistic mass increase of the individual electrons. The consequent mismatch between the beam velocity and the phase velocity of an electromagnetic wave propagating along a smooth structure basically prevents any interaction of one with the other, unless the wave is either slowed down artificially, with a periodic guiding structure, or is allowed to interact with a space-harmonic component of a periodic beam that is traveling at the correct velocity. However, no relativistic restriction exists on the velocity of the beam trace as the beam is swept, in a transverse direction, such as in a cathode-ray tube. This fact has been utilized in a device called the "Bermutron" (Ref. 52) that functions basically as a harmonic multiplier. In the most efficient version of this tube, to date, a 17-kV beam is swept linearly, at an 8.5-GHz rate, by passing it through the strong electric-field region of a coaxial cavity. The beam scans along a slotted section of rectangular waveguide, at a rate such that the injected electrons stay in phase with the traveling TE₁₀ wave. In effect, this wave is excited by the scanning beam, since the phase relationship will be such that the electrons are decelerated by the electric field and therefore give up energy to the wave. This process is enhanced further by using a resonated half-wave section of waveguide, and the mode excited in this resonator then is harmonically related to the sweep rate. With this device, 0.4 watt cw was obtained at 34 GHz, with a conversion loss of 22 db.

When one considers the interaction of the Bermutron beam with the field pattern of the half-wave resonated-guide section, it appears that this interaction is essentially the same as, though less efficient than, the excitation of a gridded-gap klystron cavity by means of a bunched beam. The scanning rate of the Bermutron beam is simply such that the strong electric field region of the resonator is phased to decelerate the beam maximally as the latter moves past this region, and clearly the total number of electrons decelerated will be less than if a longitudinally bunched beam were used.

An alternative version would have a beam scanning around a resonant-ring-type cavity and exciting a TE₁₀ wave going in one direction only. This device would be relatively large in size

and, hence, would be easier to build for use at millimeter wavelengths. However, it might be difficult to prevent serious perturbation of the waveguide field caused by the beam-injection slot, because the sizes of the beam and the waveguide will be of the same order of magnitude. Moreover, one again has a uniform beam interacting with a relatively weak electric field over a short distance, whereas it is well known that to obtain high efficiency from a beam-type device, one should inject a tightly bunched beam into a strong-field region, as in a klystron, or else one should arrange for beam-circuit interaction over a long distance, as in a TWT. For this reason one would expect this device to be less efficient than distributed-interaction periodic-beam devices, such as the cyclotron maser.

IV. BEAM-HARMONIC COUPLERS*

A bunched electron beam is inherently rich in harmonics, and the harmonic content increases with the tightness of bunching. In utilizing this effect for millimeter-wave generation, the problem then consists in the efficient extraction of harmonic power from a tightly bunched beam. In this section, we propose to discuss only those devices that couple to the harmonic power in a longitudinally bunched (O-type) beam. Magnetron harmonic enhancement has been considered in Section II. Devices that generate harmonics of the cyclotron frequency by beam interaction with transverse electric fields are discussed in Section III (Helical-Beam Devices). A swept-beam harmonic generator is discussed in Section III (Swept-Beam Devices).

The simplest way to couple to a harmonic component of a bunched (O-type) beam is to use a klystron cavity tuned to the desired harmonic. A two-cavity frequency-multiplier klystron using a 28-kV beam reportedly converted X-band power to 100 mW of output power at 120 GHz with a 23-db conversion loss (Ref. 53). However, the small size of a conventional klystron cavity that is designed to operate at millimeter wavelengths implies fabrication and voltage-breakdown problems (Ref. 54), so that other methods of coupling become attractive. In one device, the Cerenkov coupler, a high-density bunched beam is passed within close proximity of a slab of dielectric material. Radiation of energy from the beam into the dielectric takes place if the beam velocity is greater than the speed of light in the dielectric. This device generally requires relativistic beams (Refs. 55,56). Despite considerable theoretical effort on the subject, the measured performance of Cerenkov couplers has been unimpressive so far. The current state of the art is given reasonably well by the results reported by Coleman and Enderby (Ref. 57) who produced 1 watt at 37 GHz with a 900-kV beam, bunched at S band, grazing a slab of Teflon dielectric. Coleman (Ref. 58) has pointed out that further improvement in the efficiency of Cerenkov couplers is basically a materials problem in that it hinges on the development of some solid, nonmagnetic, dielectric material with a tensor dielectric constant.

A modification of the Cerenkov-type coupler was used by Hakki (Ref. 59) who let a 0.8-MeV, S-band-bunched beam impinge normally on a copper target, thereby getting a combination of Cerenkov radiation and Bremsstrahlung at high harmonics of the bunching frequency. (Bremsstrahlung radiation can be considered as arising from the "annihilation" of charge as the electron bunch and its image charge meet on the target surface.) Hakki

*Longitudinally bunched beam

obtained coherent bursts of radiation with small components at frequencies near and above 120 GHz. However, this approach does not seem to be an improvement on pure Cerenkov-type couplers, and no further work has been reported along this line.

Still another way to couple harmonic energy from a bunched linear beam was first introduced by Motz (Ref. 60) who suggested the use of a magnetic undulator that would cause the electron beam to follow a sinuous path under the influence of a stationary transverse magnetic field pattern. Motz, Thon, and Whitehurst (Ref. 61) generated a visible light in an undulator using 100-MeV electrons from a linear accelerator, and Motz and Mallory (Ref. 62) generated submillimeter radiation with a magnetic undulator using a 2-MeV beam bunched at S-band. One might note that even an unmodulated electron beam that is made to travel through an appropriate electric or magnetic field pattern will radiate energy. The frequency spectrum of the emitted radiation then depends on the speed of the electrons and on the periodicity of the stationary field pattern (Ref. 63). However, when a bunched beam is used, then the radiated output is harmonically related to the bunching frequency, although the peak of the emitted spectrum still depends on beam velocity. This is the situation with the greatest practical value, since megavolt beams are most easily generated with rf accelerators, and beam-bunching at the accelerator frequency is therefore implied.

The most recent undulator results are probably those of Miller (Ref. 64) who obtained 30-mW at 1-mm wavelength, using a 4-MeV beam bunched at X-band. The great bulk of Miller's equipment (linear accelerator) is not necessarily typical, however, as rf acceleration of a linear beam can also be achieved in a more compact way by passing the beam through a single cavity that has been excited in a high axial mode. A device of this type, called the "Rebatron," was first demonstrated by Coleman (Refs. 65, 66).

There is a great temptation to classify the "Ubitron," that was discussed earlier, as simply another undulator that couples to the fundamental signal component on the bunched beam rather than to a beam harmonic. However, this is not quite correct because the Ubitron functions as a traveling-wave amplifier, i.e., it first bunches the initially smooth beam and then extracts rf power from it, whereas an undulator, as described here, is merely an output coupler operating on a prebunched beam. Nevertheless the trade-off between the periodic spacing of the undulator pattern and the beam voltage, for a given output frequency, is probably similar for the two devices. Thus, one might expect that an adaptation of the undulator to work at lower beam voltages, while desirable, would necessitate a closer spacing of

the magnet array and hence, would lead to similar problems of magnetic saturation and leakage as with the Ubitron.

An interestingly different version of the undulator was first suggested by R-Shersby-Harvie (Ref. 67) and later reduced to practice by Sirkis and Wang (Ref. 68). The basic idea is to replace the beam-perturbing field of the magnetic-undulator pattern by the electromagnetic standing-wave field of a resonant cavity that is driven by an external source of frequency f_1 , for example. The cavity is simultaneously resonant at a higher frequency f_2 . The beam, which is assumed to be bunched at some frequency f_0 , is passed through this cavity. By means of an interaction that can be analyzed in terms of the Doppler effect, an oscillation is excited in the cavity at frequency f_2 , where $f_2 = f_1 + n f_0$ with n an integer. Clearly, if $f_1 = 0$, one gets back the zero-frequency (e.g., magnetostatic) undulator, and the latter is thereby recognized as a special case of this more general mechanism.

In their experimental device, Sirkis and Wang (Ref. 68) passed a relativistic beam, bunched at 3 GHz, through a cavity that was driven in a circular TE_{101} mode at 9 GHz. This, in turn, excited the $TE_{3,0,10}$ mode at 40 GHz, and 2.4 mW were extracted at this frequency. The high measured conversion loss (75 db) clearly points to a basic inefficiency of this mechanism, and the device therefore seems to have little practical value. Sirkis' and Wang's device could be considered as a different version of Coleman's early "Harmodotron" coupler (Refs. 69, 70). The latter device was based on the idea of getting the beam to interact with a high axial mode of an (otherwise passive) output resonator. Not much work seems to have been done beyond the early feasibility tests on the Harmodotron. In any case, it appears that the simultaneous excitation of more than one axial resonance in the cavity could create serious difficulties both in the Harmodotron and in the Sirkis-Wang coupler.

In summary, the results obtained to date with O-type harmonic couplers indicate that very little progress has been made in the last decade with non-conventional mechanisms, such as Cerenkov or undulator-type couplers. Conventional two-cavity klystron multipliers, on the other hand, have been rather successful. It may well be possible to enhance the conversion efficiency and/or the power-handling capacity of klystron multipliers by using a distributed-interaction output cavity. In effect, this would be a Harmodotron device, except that better mode control may be possible by judicious strapping of the slow-wave circuit, and stronger axial fields should be obtainable. At the same time, an O-type distributed interaction harmonic generator might produce less noise than the magnetron-type devices discussed in Section II.

V. CONCLUSION

The purpose of this report has been to assess the capability of beam-type devices for coherent power generation in the millimeter-wave region. The problem has been approached by dividing the large body of existing devices into three functional groups, i.e., periodic-circuit devices, periodic-beam devices, and beam-harmonic couplers.

The present state of the art is essentially dominated by periodic-circuit devices such as BWO's and TWT's (Figures 1 and 2). Although there seems to be no basic physical threshold to block further extension of these conventional devices to higher frequencies and power levels, it is clear that such an extension is faced by increasingly difficult problems of beam formation and structure fabrication. Further technological development must therefore take place in a regime of diminishing returns.

Magnetrons operating in the fundamental mode are subject to limitations similar to those of TWT's and BWO's. However, the traditionally high harmonic output of magnetrons, when suitably enhanced by modifying the anode structure, can serve as a very simple, though probably somewhat noisy, source of millimeter-wave power. The relatively modest development efforts along this line have been quite successful.

DC-pumped transverse-wave tubes appeared quite promising at first because of their frequency-independent gain mechanism. However, the early expectations proved unjustified, mainly because of unexpected problems of beam control which are peculiar to this type of tube. Most work on these tubes has therefore been abandoned.

The problems of fabricating delicate slow-wave structures can be avoided by using an approach in which a periodically deformed beam is allowed to interact with the electromagnetic fields supported by a smooth waveguide. The most successful devices of this type are those in which the required periodic motion is generated before the beam has either reached high velocities or has entered regions of strong magnetic field. This is done, for example, in the cyclotron maser and in the planar smooth-anode magnetron, both of which show great potential for further development. In addition, the cyclotron-maser mechanism is inherently well suited for the generation of almost-optical submillimeter radiation. The latter may occur either at the cyclotron frequency or some multiple thereof, depending on the available magnetic field strengths.

The efficient extraction of harmonic power that is inherently contained in a tightly bunched beam forms the basis of O-type beam-harmonic devices. Despite considerable development effort on Cerenkov and undulator-type couplers, little progress has been made with these devices. The state of the art is still governed by conventional two-cavity klystron multipliers, and these tubes are limited, of course, by the problem of decreasing dimensions. It may be possible to relieve the latter problem somewhat by using distributed-interaction resonators.

In summary, on the basis of past development effort and best measured performance, one concludes that periodic-beam devices -- in particular, cyclotron masers -- have the greatest potential as high-power millimeter and submillimeter-wave sources. Pending further development of these sources, good stop-gap service can be expected from existing ultra-refined versions of conventional O-type BWO's and TWT's, from frequency-multiplier klystrons, and from magnetron-harmonic generators.

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APPENDIX

A CRITIQUE OF TRANSVERSE-WAVE TUBES FOR POSSIBLE MILLIMETER-WAVE APPLICATION

INTRODUCTION

While significant advances have recently been made in the extension of conventional space-charge or longitudinal-wave amplifiers and oscillators into the millimeter-wave region, it has been clear for some time that progress is severely limited by the increasing difficulty of fabricating the necessary slow-wave structures and of steering a very dense electron beam sufficiently close to such a structure to produce significant interaction. Efforts have thus been made to produce alternative methods of millimeter-wave generation.

It is the purpose of this Appendix to make a critical evaluation of one of these techniques, that is, the interaction of a linear electron beam with transversely directed RF fields.

There are, in fact, many different ways in which such interaction can take place, and a unified approach can best be obtained by making use of the coupled-mode theory (Refs. 71-76)*. It is well known that the behavior of an electron beam where motion is restricted to the axial coordinate can be described by superimposing appropriate amplitudes of the fast and slow space charge waves, and these constitute the normal modes for such a beam. If transverse variations are also allowed, then more normal modes are needed to completely describe beam behavior.

The simplest case of this type is a filamentary beam immersed in an axial magnetic field, acted upon by transverse electric fields. It can be shown that such a beam will support four normal modes of transverse variation. These are, first, the two cyclotron waves, corresponding to electrons rotating about the beam axis at the cyclotron frequency as they drift forward with an axial velocity equal to the dc beam velocity. Second, there are the two synchronous or displacement waves which correspond to fixed helical patterns of electrons drifting at dc beam velocity, and thus creating a wave effect when seen by a fixed observer. It is not necessary here to dwell on the possible ways of exciting these waves, but it will be helpful to look at their respective energy levels. Using the energy level of the dc beam as a reference, it can be shown that the

*See list of references at end of main body of text.

slow cyclotron wave and one of the displacement waves carry negative energy. The analogy with the fast and the slow space-charge waves is obvious. It will be seen, however, that the filamentary beam is not as good a model for transverse interaction as is the axially confined beam for longitudinal interaction. Finite-thickness beams can support additional normal modes (Refs. 17-19, 77-78). Nevertheless, the normal modes of the simple filamentary beam have served as a convenient means for classifying the existing types of interactions as well as for discovering new ones.

As early as 1948, J. R. Pierce (Ref. 79) discussed the cumulative interaction of a transverse-field slow-wave structure with the cyclotron waves of a linear electron beam, as a natural extension of his longitudinal-field theory. However, since the transverse interaction impedance is generally smaller than the longitudinal impedance, the device possibilities suggested by Pierce's analysis were rather unattractive and remained largely unexplored. In one experimental tube (Ref. 80) the small transverse interaction impedance of a pin-type slow-wave circuit was enhanced, in effect, by using resonated sections of this structure along the beam, making the device essentially a klystron. Interaction occurred with the synchronous waves of a near-filamentary beam. A moderate amount of gain was obtained, but higher gain could not be achieved because of beam interception by the slow-wave structure. In a different experiment (Ref. 81), a gain of 10 db was obtained at 2950 MHz from a transverse-wave TWT, using cumulative interaction between a meander-line structure and the slow cyclotron wave.

A major breakthrough came when the invention of the Adler tube (1958) demonstrated that the transverse motion of electrons could be amplified parametrically, so that the amplification of the beam waves no longer had to depend on cumulative interaction with a slow wave structure (Refs. 82-85). In an Adler tube, the fast cyclotron wave is excited (and beam noise is removed) by a Cuccia coupler (Ref. 86). The wave is then amplified parametrically as it passes through a quadrupole field which is pumped at twice the signal frequency, and the signal is finally extracted from the beam by means of another Cuccia coupler. While the primary advantage of the Adler tube was simply its low noise figure, the idea of beam interaction with a quadrupole field was quickly explored further, as this represented a gain mechanism which was independent of frequency, and therefore useful, in principle, even at very high frequencies (Refs. 87, 88).

One inconvenient feature of the Adler tube, i.e., its need for a pump source at twice the signal frequency, was overcome with the discovery (Ref. 89) that the transverse energy of the beam electrons could also be amplified by passage through

an appropriate inhomogeneous electrostatic field, such as that produced by a quadrupolar helix. One then has, in effect, a series of small electric quadrupoles which are staggered in a helical pattern along the beam, with a pitch such that an electron drifting along with the beam sees an apparent field variation at twice the cyclotron frequency, just as in the case of the time-varying pump fields of the Adler tube.

The theory of dc pumping was put in very general terms when it was shown (Ref. 90) that amplification of the transverse beam waves could be achieved not only with static electric or magnetic fields of quadrupolar symmetry, but also with axially symmetric periodic fields. In coupled-mode language, the normal modes of transverse beam excitation are coupled together parametrically by the action of an equivalent pump "wave" which acts on the electrons as they drift through the periodic electrostatic or magnetostatic field. Gain results purely from this coupling of positive and negative-energy waves, and the dc energy of the beam remains constant during this process, at least in the small-signal approximation. However, when an output signal is finally obtained by stripping the positive-energy wave from the beam, then this amounts to a conversion of dc beam energy into RF energy, and the beam is consequently slowed down by the output coupler. The details of which waves are excited, coupled to one another, and then extracted from the beam, depend on the design characteristics of both the couplers and the pump structure. For the excitation of any waves other than the fast cyclotron wave, it is necessary to use periodic-circuit couplers. The pump structure required for dc pumping must always be periodic, and the dimensions of both couplers and pump structure decrease with increasing frequency. Therefore, although the gain mechanism of these amplifiers is frequency-independent, with the bandwidth limited only by their coupler characteristics, the necessity for periodic structures represents a serious limitation for millimeter-wave application of these tubes.

Many experimental investigations have been made -- some of them very comprehensive -- to evaluate all the different types of mode cross-coupling which can occur under dc pumping. Following the successful translation of the original Adler tube into the microwave region (Ref. 87), there was considerable optimism about the possibilities of transverse-wave amplifiers in general. In particular, it was claimed that the efficiency could be very high, because the simple theory predicted zero velocity spread in the spent beam. The argument was that after stripping of the fast-wave energy from the beam, the remaining modulation would contain only one wave component, thus making the beam mono-energetic. A depressed collector then would collect the electrons at close-to-cathode potential, and this would achieve high efficiency. Experiments did not, however, confirm this theory (Refs. 91-101). The fallacy of the argu-

ment became clear when it was found (Ref. 19) that transverse waves are not necessarily mono-energetic, and that a single transverse wave may be accompanied by a longitudinal velocity spread representing a power comparable to the RF power carried by the wave. Actually the entire controversy was somewhat academic, because both the gain and the efficiency of most of the experimental devices were limited not by velocity spread but by beam interception in the pumping region. Only one case has been reported in which this was not so, i.e., in which the beam reached true transverse saturation before interception by the pump structure (Ref. 97). However, this experiment involved a rather critical alignment of beam scallops with the transverse field pattern of an external magnetic pump structure, and later attempts to duplicate these results elsewhere failed (Refs. 98-100).

The "Larmotron" project at SFD laboratories (Ref. 99) was the most recent experimental program for the study of transverse-wave interaction, and provides a good illustration of the problem of beam control. One difficulty was caused simply by the finite thickness of the beam and the resultant excitation of beam waves other than those predicted by the filamentary model. However, the main difficulty again was beam expansion in the pump structure.

Beam expansion in the pump structure arises as follows. The large cathode-convergence ratios necessary to generate high-power beams with millimeter-wave dimensions generally entail a shielded gun design; the beam then acquires a rotational motion when it enters the magnetic-field region. For practical beams, with a confining magnetic field somewhat greater than the Brillouin value, it turns out that the rate of dc beam rotation is sufficiently close to the cyclotron frequency to cause the motion to be amplified by the pump field. As a result, the beam diameter grows until interception occurs. (For completeness, it should be mentioned that beam-interception problems were not in all cases traceable to dc pumping of the beam diameter. In some of the experiments involving magnetostatic pumping (Refs. 97, 98, 100) beam misalignment was caused simply by the perturbation of the longitudinal magnetic field in the presence of the pole pieces of the pump structure.)

Some time ago, it was found (Refs. 102-104) that the problem of dc beam instability in the pump region could be solved -- in theory, at least -- by increasing the space-charge density in the beam. This would occur automatically in millimeter-wave beams which, in general, have high current densities. However, experiments so far have failed to confirm this theory, and beam instability remains a major unsolved problem in dc-pumped tubes.

As Wessel-Berg (Ref. 105) has pointed out, the dc-stabilized beam is at best held in unstable equilibrium because the high space-charge density necessary for dc stabilization may be upset locally from either longitudinal or transverse RF debunching forces or even from noise on the beam. Once this happens, the instability may build up and may again destroy the beam.

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